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OFFICE NOTE 14

JNWP 12-HR AND 24-HR UPPER-LEVEL WIND FORECAST ERRORS

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I. INTRODUCTION

Upper level verification studies have been made in the past which measure the validity of conventional forecast techniques. Forecast errors computed from such studies depend to some extent upon the forecasters' training and experience as well as the particular forecast techniques employed. In the case of numerical forecasts the errors are related to the type of prediction model used. This type of wind error might be classed in the category of the forecast technique employed. Furthermore, wind errors vary with the seasons and this variation is related to the varying behavior of the atmosphere with the seasons. Superimposed upon these seasonal trends there exists daily fluctuations. Validity of forecasts over different geographical regions probably vary to some extent also. And, of course, when verifying geostrophic forecast winds vs. reported data, the observational errors and ageostrophic motions also influence the computed forecast error.

All of the above error-influences should be carefully considered when one wind verification study is weighed against another.

12-hr and 24-hr forecasts of the 850-mb, 500-mb, and 300-mb winds (geostrophic) over a portion of North America were verified in this study for the months of February, March, and April of 1959. The 500-mb forecasts were made by the JNWP operational equivalent barotropic model which has incorporated into it a scheme of very long atmospheric wave stabilization [1]. The flow was balanced initially. The 850-mb forecasts were obtained by a model which was designed by Thompson [2]. The operational version has been simplified considerably. First of all the 500-mb level is forecast barotropically and no "feed-back" from the lower level is allowed to influence this level. Terrain effects are present empirically in the barotropic forecast but not in the thickness forecast equation. Static stability is treated as a constant in both time and space, and surface vertical velocities are assumed to be zero. Thus the 500-850 mb thickness is forecast keeping the 500-mb level fixed barotropically, and an 850-mb forecast is obtained.

The 300-mb forecast is one that is actually a by-product of the two-level "meshed" model. The 850-mb and 500-mb forecast heights were used to obtain extrapolated 300-mb heights. The deviation of the thickness from the standard atmosphere was utilized and then a slight modification applied.

II. PURPOSE

This verification study was undertaken to obtain an objective estimate of the accuracy of certain short-range wind forecasts. It is also an attempt to show the amount of error in the numerical prognoses and compare these errors with those made by conventional methods. No attempt has been made here to express the errors as functions of geographical location or season.

III. PROCEDURE

The test applied to the forecast winds was a very rigid one in which the geostrophic forecast winds were verified against the reported winds. All calculations were done on the IBM 704 electronic computer.

TABLE 4. A comparison of the 300-mb extrapolated "analyses" and forecasts and the 300-mb machine analyses. The unit is knot.

STATISTICS		300 MB (extrapolated)			300 MB (analyzed)		
		Observed	12 Hr	24 Hr	Observed	12 Hr	24 Hr
F	$\overline{\lvert WE \rvert}$	23.2	27.1	31.9	18.2		
H	RMS(WE)	27.2	30.8	37.0	21.0		
J	RMS(W_{gs})	66.5					
K	RMS(W_{gs}D)		25.2	38.2			

It was desirable to make this study over a region of dense data coverage. The region considered was one enclosed by the JNWP octogonal grid from I=12 to I=29 and J=6 to J=17. This encompasses the United States (excluding Alaska and Hawaii) and the southern portion of Canada. Forecasts were verified at 1200Z on all even days from February 10 through April 10. The reported wind data which went into this study were the same data which are processed by the automatic data processing system presently employed by the JNWP Unit. All winds are machine-checked for vertical consistency. When a wind did not meet the criteria necessary for use in the machine analysis, it was not considered in the verification study.

The geostrophic forecast winds were computed at the grid points using centered finite differences. For each observation the four surrounding geostrophic forecast winds were linearly extrapolated to obtain a forecast value at the observation location. This wind was then compared with the reported wind. Based on findings by Carstensen [3] it was felt that for a long period of time little would be gained by using the 500-mb forecast stream function rather than the 500-mb heights. Of course it is quite possible that day-to-day variations exist over the region considered.

In addition to the statistics obtained from such a comparison as the above, it was also desirable to obtain a measure of the persistence of the observed wind. For an estimate of this the root-mean-square (r.m.s.) vector difference of the geostrophic winds from the initial analysis and the analysis 12 hours previous over the region involved was computed using the grid-point values. This type of measurement was also made for a 24-hr persistence estimate.

The r.m.s. of the geostrophic winds of the initial analysis was also computed with the program mentioned above. This gave a measure of the average strength of the geostrophic wind at the level involved and over the region under verification.

Consider the u and v components of the wind parallel to the I and J axis of the octagonal grid. The subscript o shall refer to the reported wind, and the subscript f shall refer to the forecast wind. The number of sets of data will be denoted by N. Due to the orientation of the octogonal grid the u-component of the wind approximates the zonal flow over the region considered. The following statistics were obtained from data at observation locations:

A. Average u-component of the wind.

$$\bar{u} = \frac{1}{N} \sum u$$

B. Average v-component of the wind.

$$\bar{v} = \frac{1}{N} \sum v$$

C. Average magnitude of the whole wind.

$$\bar{V} = \frac{\sum V}{N} = \frac{1}{N} \sum (u^2 + v^2)^{1/2}$$

D. Average sine of the angle (γ) between the forecast and reported wind. The average sine of the obtuse angle is positive when measured counter-clockwise from the forecast wind vector to the reported wind vector.

$$\overline{\sin\gamma} = \frac{1}{N}\sum \frac{u_f v_o - v_o v_f}{V_f V_o}$$

E. R.m.s. of the wind.

$$RMS(V) = \left[\frac{1}{N}\sum (u^2 + v^2)\right]^{\frac{1}{2}}$$

F. Average magnitude of the vector error.

$$\overline{|VE|} = \frac{1}{N}\sum \left[(u_o - u_f)^2 + (v_o - v_f)^2\right]^{\frac{1}{2}}$$

G. R.m.s. $\underline{u}$ error.

$$RMS(uE) = \left[\frac{1}{N}\sum (u_o - u_f)^2\right]^{\frac{1}{2}}$$

H. Magnitude of the r.m.s. vector error (standard vector error).

$$RMS(VE) = \left\{\frac{1}{N}\sum \left[(u_o - u_f)^2 + (v_o - v_f)^2\right]\right\}^{\frac{1}{2}}$$

I. Vector error expressed as a direction error. This quantity was computed using $\overline{|V_o|}$, $\overline{|V_f|}$ and $\overline{|VE|}$.

The above statistics represent a comparison of geostrophic winds vs. reported winds. The following quantities were obtained from analyzed geostrophic winds

J. R.m.s. of the analyzed wind. $RMS(V_{gs})'$

K. R.m.s. vector difference. $RMS(V_{gs}\ D)$

This is the measure of analysis persistence.

The results of this study are given in Table 1. Winds are expressed in knots. All statistical quantities containing reported winds (except $\bar{\bar{v}}$ and $RMS(V)$) were obtained from 2992 sets of data at 850 mbs, 2116 sets at 500 mbs, and 1206 sets at 300 mbs. The $\bar{\bar{v}}$ quantities contained 768, 546, and 291 sets at 850 mbs, 500 mbs, and 300 mbs, respectively, collected from February 10 through February 26. The $RMS(V)$ quantities contained 1197, 855, and 519 sets at 850 mbs, 500 mbs, and 300 mbs, respectively, collected during the remainder of the period. $RMS(V_{gs})$ and $RMS(V_{gs}, D)$ were obtained from 29 days of data. (March 8 data was disqualified in this report due to analysis difficulties.)

Using R. Murray's and D. H. Johnson's wind verification results, Sutcliffe and Sawyer [4] reported similar wind statistics which were obtained over the British Isles and the adjacent Atlantic for a trial period in Spring. The forecast technique employed was a conventional one which incorporated a method of thickness advection with the mean wind. The 24-hr, 500-mb and 300-mb r.m.s. vector errors are given in row L of Table 1. The 24-hr r.m.s. vector difference of the observed winds are given in row M.

IV DISCUSSION OF RESULTS

It should be emphasized that the results are only meant to give some indication of the validity of the JNWP Unit forecasts and are not strictly valid for all locations in the grid or at all times. One might suppose that the annual average errors over the U. S. and Southern Canada would be somewhat less than those found in this study since this sample was composed of data from late winter as well as early spring.

From row C and D of Table 1, it is possible to say something about the wind errors in terms of speed and direction. The fact that the algebraic average of the angles between forecast and observed wind vectors was small tells us simply that the direction of the vector error of the numerical forecasts was random - i.e., the wind forecast vector did not tend to deviate more in one direction than the other from the observed wind. It should be mentioned here that it was assumed that the angle computed from each pair of winds was an obtuse angle. In most cases where this assumption is invalid the winds are likely to be weak. The fact that at each level the average magnitude of the observed and forecast winds are about the same signifies that the wind magnitude was forecast too strong as often as it was forecast too weak, and the forecast average was approximately constant with time. Thus the average magnitude of the geostrophic forecast wind over this two-month period and over the particular region approximated the average observed wind magnitude quite closely. This of course does not show us if there was a consistant discrepancy between forecast and observed wind magnitudes locally within the region. For example, it does not tell us if the forecast wind gradients in the vicinity of the jet stream is under-forecast or if the gradients are over-forecast on the periphery of the jet.

The r.m.s. observed winds at the three pressure surfaces (E) differ somewhat from the r.m.s. geostrophic analyzed winds (J). These differences might possibly be attributed to the fact that the analyzed values were computed at the grid points rather than at the observation points. Of course another possible explanation of the differences of E and J might be due to the fact that one is from observed winds while the other is from geostrophic winds. Carstensen also found that the geostrophic winds were stronger (3%) than the observed winds, and he attributed this to be due to the analysis procedure which considers the observed winds as being 8% sub-geostrophic.

As stated in the previous section the quantities reported in row I of Table 1 are angles which are computed from the average magnitudes of the vector forecast, vector observed and vector error winds. Since the average magnitudes of the observed and forecast winds are almost equal, these angles represent the vector errors expressed as direction errors. This does not mean that these angles represent the average error in direction. This would be the case only if the individual wind speeds (at each observation point) were correctly forecast.

According to Murray [5] a good estimate of the percentage of the wind variation which is correctly forecast is given by the formula:

$$100\left[\frac{K^2-H^2}{K^2}\right]^{1/2},$$

where H is the r.m.s. forecast error and K is the r.m.s. of the wind variation. This measure of skill was applied to the results of this study and to the results of Sutcliffe and Sawyer's report. In addition, Ellsaesser [6] compiled wind forecast verification data (which was obtained from a large sample and which included Sutcliffe and Sawyer's sample) which represented an annual average for the latitude belt from 25°N to 65°N. These results are presented in Table 2.

Sutcliffe and Sawyer's and Ellsaesser's figures are presented only to give a general comparison. A strict comparison cannot be made since the data are different. Furthermore, their persistence measurements were made from the observed winds while the persistence measurements of this study were obtained from geostrophic analysis persistence at the grid points. Persistence measurements from observed winds would probably be larger than persistence measurements from analyzed maps since observed winds contain random observational errors.

The fact that the 12-hr 300-mb forecast showed no skill whatsoever may be attributed to, among other things, the crude method of measuring persistence and, most important of all, the fact that the 300-mb level is not mathematically incorporated into the forecasting model.

The magnitude of the average vector error (F of Table 1) may seem quite large to the forecaster using JNWP forecasts. Of course one must bear in mind the fact that this method of evaluation of the errors does not filter and separate out observation errors, analysis errors, or errors which result from comparing observed winds with geostrophic winds.

In order to get an estimate of the magnitude of these errors, the verification program was applied to a few cases in which the analyses were verified against the observed data. The average results for the four days considered (18 February, 18 March, 22 March and 2 April) are presented in Table 3 under the "observed" column. The letters have the same statistical meanings previously defined and all values are in knots. The 12-hr and 24-hr forecast values are also presented in this table. During these four days and over the same region of verification, there were 404, 289, and 168 observed winds at the 850-mb, 500-mb, and 300-mb levels respectively.

Sutcliffe and Sawyer reported a r.m.s. vector error in the hand analyses of the British sample of 14 kts and 20 kts. for the 500-mb and 300-mb levels respectively. Their 24-hr persistence values were 35 kts. at 500-mb and 48 kts. at 300-mb. These figures may be generally compared with the values of 14.0 kts. and 29.3 kts. obtained from the present study. The validity of the JNWP 300-mb extrapolation will be discussed in more detail later.

Notice that the vector errors of the analyses are by no means small in comparison to the forecast errors. If we say that an otherwise perfect forecast cannot exceed the quality of the analysis, then the magnitude of the vector errors in the 850-mb, 500-mb, and 300-mb 24-hr forecasts differ from a perfect forecast by 6.3 kts., 6.8 kts., and 6.7 kts., respectively. These values, of course, apply specifically to these four 1200Z cases. It is of interest to note here that a wind direction error of 5 degrees in a 70-kt wind produces a vector error of 6.1 kts. Wind directions are normally given to the nearest tens of degrees. This type of reasoning leads one to believe that the forecasts are as a whole quite good.

We may go even further in our evaluation of the 300-mb extrapolated forecasts. Two machine analyses (18 February and 2 April) were made at 300-mb and compared with the extrapolated maps. The results are given in Table 4 together with the 12-hr and 24-hr forecast errors. There were 76, 300-mb observations received during these two days for 1200Z within the verification region. Here the average vector error of the true analysis was 5 kts. less than the extrapolated error. It can be seen from Table 4 that the average 24-hr forecast vector error is 13.7 kts. greater than the average vector error of the winds in the true analyses and only 8.7 kts. greater than the average vector error of the winds in the extrapolated analyses. Therefore, based on these two cases it appears that the 6.7-knot, 300-mb error found for the four cases discussed above might be an underestimate. Thus, it is apparent that the 300-mb analyses show considerable improvement over the extrapolated maps.

It is necessary to point out that forecast wind errors over a route are less than spot wind forecast errors. Sutcliffe and Sawyer estimated that for a 1200-mile route the route wind errors are about two-thirds those of spot wind forecasts. This is due to the fact that in the case of route winds the errors tend to cancel.

V CONCLUSION

As has been mentioned previously, it is difficult to make a strong comparison between the statistical results of this study and those of previous studies since the data upon which the studies are based are different and in some cases the method of comparison differs considerably. Thus from the results of this study, it is difficult to state conclusively whether these JNWP products are better or worse than the forecasts made by conventional means. Nevertheless from the results of this study, it is evident that considerable skill is expressed by the JNWP shorter range upper-level wind forecasts. The exception to this statement is the 12-hr 300-mb forecast. The difficulty here seems to lie for the most part in the fact that this chart is a by-product of the operational model and is not mathematically incorporated into the forecasting system.

It appears that the 500-mb forecasts from the equivalent barotropic model express more of the wind variation than does the 850-mb or 300-mb forecasts.

The vector errors increase with height. This is due mainly to the fact that the wind magnitudes increase considerably with height.

The forecast errors do not increase as rapidly as does the wind variation from 12-hrs to 24-hrs. This is evident from the fact that the forecast skill, as measured in this study, is larger for the 24-hr forecasts.

The forecasts under consideration did not show a tendency to deviate systematically in direction or magnitude. This of course does not mean that local deviations do not exit.

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TABLE I. WIND STATISTICS.

All winds are in knots. See text for symbolic meanings.

STATISTICS		850 MB			500 MB			300 MB		
		Observed	12 HR	24 HR	Observed	12 HR	24 HR	Observed	12 HR	24 HR
A	$\overline{u}$	10.8	12.0	12.8	29.5	31.4	31.9	45.4	47.6	48.5
B	$\overline{v}$	4.3	3.9	1.4	8.0	7.7	8.8	22.3	19.5	21.5
C	$\overline{V}$	19.6	19.0	19.9	39.8	40.3	40.6	59.7	60.4	60.4
D	$\overline{\sin\gamma}$		+0.0325	-0.0009		+0.0047	-0.0216		+0.0406	+0.0121
E	RMS(V)	21.5	21.6	23.2	40.2	39.0	39.4	60.5	59.2	59.3
F	$\overline{\lvert VE \rvert}$		11.8	14.7		14.7	17.9		26.1	27.9
G	RMS(uE)		9.1	11.7		12.4	15.2		20.7	23.2
H	RMS(VE)		13.8	17.2		17.7	21.5		28.7	32.5
I			35.7°	46.5°		21.5°	25.7°		25.0°	26.9°
J	RMS(V_{gs})	22.1			44.2			68.4		
K	RMS(V_{gs}D)		14.8	21.8		20.8	29.9		28.4	41.7

SUTCLIFFE AND SAWYER'S FINDINGS

L	RMS(VE)						27			33
M	RMS(VD)						35			48

TABLE 2. Skill estimates using R. Murray's formula.

	850 MB		500 MB		300 MB	
	12 Hr	24 Hr	12 Hr	24 Hr	12 Hr	24 Hr
JNWP	36%	61%	53%	69%	0%	63%
Sutcliffe & Sawyer				64%		74%
Ellsaesser				64%		73%

TABLE 3. Comparison of analyzed winds vs. reported winds and forecast winds vs. reported winds. The unit is knot.

STATISTICS		850 MB			500 MB			300 MB (extrapolated)		
		Observed	12 Hr	24 Hr	Observed	12 Hr	24 Hr	Observed	12 Hr	24 Hr
F	$\overline{\lvert VE \rvert}$	8.8	11.9	15.1	11.8	16.1	18.6	24.7	28.5	31.4
H	RMS(VE)	10.4	13.8	17.3	14.0	18.8	23.1	29.3	32.5	36.3
J	RMS(V_{gs})	21.8			46.1			69.5		
K	RMS(V_{gs}, D)		14.4	22.1		19.9	30.6		28.0	43.5